LHCb measurements of ϕ_s

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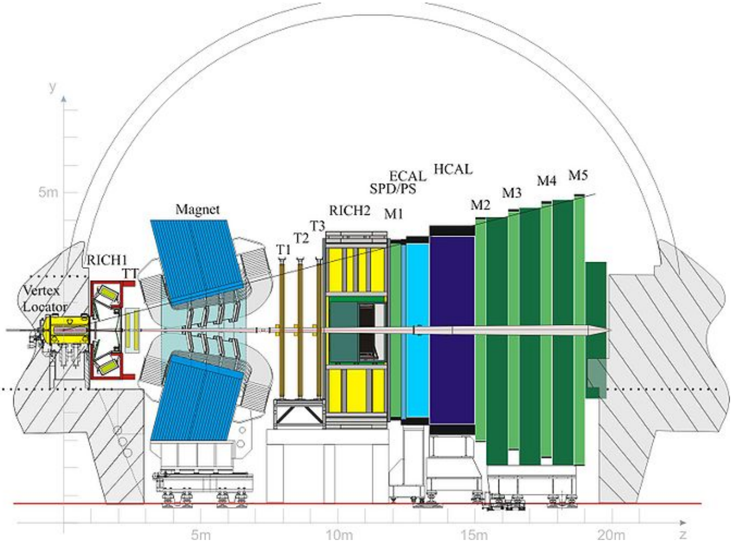
Presentation on behalf of LHCb collaboration

Phenomenology 2012 Symposium

Contents

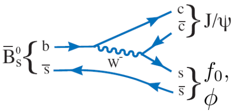
- Measurement of CP violation is a very important goal of LHCb. This talk presents new LHCb results on ϕ_s measurements, using full 1 fb^{-1} of data from 2011.
  - CPV ϕ_s from $\overline{B}_s^0 \rightarrow J/\psi\pi^+\pi^-$. arXiv:1204.5675, submitted to PLB
  - CPV ϕ_s, $\Delta\Gamma_s$ and other quantities from $B_s^0 \rightarrow J/\psi\phi$. LHCb-CONF-2012-002
  - Combining the ϕ_s measurements from $\overline{B}_s^0 \rightarrow J/\psi\pi^+\pi^-$ and $B_s^0 \rightarrow J/\psi\phi$. LHCb-CONF-2012-004
  - Resolving the **two fold ambiguity** for ϕ_s, $\Delta\Gamma_s$. arXiv:1202.4717, submitted to PRL
  - ϕ_s from other decay modes.

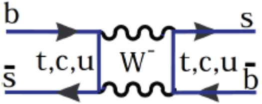
LHCb Detector

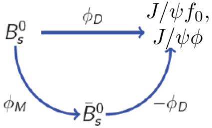


CP violation in B_s^0 decays

- B_s^0 decays to $J/\psi\phi$ or $J/\psi\pi^+\pi^-$ dominated by tree diagrams, with a single decay phase ϕ_D. (In SM and ignoring penguin $\phi_D \sim 0$.)
- Before decaying to final state, B_s^0 mesons can also first oscillate into $\overline{B}_s^0$ with a mixing phase ϕ_M.
- The **interference** between the decay and mixing give rise to the CPV phase: $\phi_S = \phi_M - 2\phi_D$.
- In SM ϕ_s prediction is small and precise: (PRD 84 (2011) 033005)
  $\phi_S^{\mathrm{SM}} = -2\beta_s \sim -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.036 \pm 0.002$ rad.
- **New Physics can add large phases:** $\phi_s = \phi_s^{\mathrm{SM}} + \phi_s^{\mathrm{NP}}$**,**
  $\Rightarrow$ **measurement of ϕ_s therefore can probe New Physics.**







Signal for CP violation

- The decay time evolution

$$\propto e^{-\Gamma_s t}\{\cosh\frac{\Delta\Gamma_s t}{2} + \cos\phi_s \sinh\frac{\Delta\Gamma_s t}{2} \pm \sin\phi_s \sin(\Delta m_s t)\} \quad (1)$$

  - Sinusoidal term in proper time distribution. Good proper time resolution is required for time dependent analyses with fast mixing frequencies $\Delta m_s = 17.63 \pm 0.11 \pm 0.02\ \mathrm{ps}^{-1}$ (PL B709 (2012) 177).
  - Amplitude is proportional to $\sin\phi_s$.
  - Opposite sign for B_s^0 and $\overline{B}_s^0$, must tag.
  - High statistics, good signal purity and efficiency needed to reach SM predictions in noisy environment.

- LHCb was built precisely for this purpose.

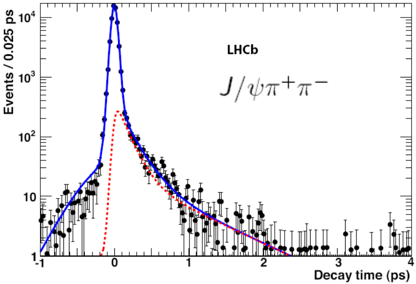
Flavour tagging

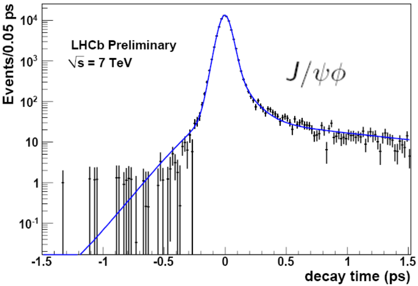
- Time dependent CP asymmetry needs to identify the initial flavour of reconstructed B_s^0 mesons (initial state a b or $\overline{b}$ quark). $\Rightarrow$ **Flavour tagging**.
- Opposite Side (OS) tagging is used in ϕ_s measurement.
- OS algorithm exploits the **anti-correlation** between the B hadrons produced in the same event, by looking the decay products of the opposite B (tagging B).
- The correlation method has an **intrinsic dilution** on the tagging decision due to the possibility of **flavour oscillation** of the tagging B_s^0 mesons. It is calibrated by using the flavour specific decay $B^+ \to J/\psi K^+$.

- Effective Tagging power, $\epsilon_{\rm tag} D^2 = (2.43 \pm 0.08 \pm 0.26)\%$ (arXiv:1204.5675).

Decay time resolution

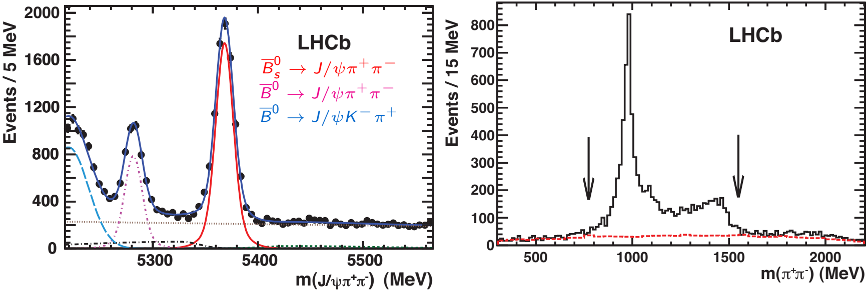
- Time dependent CP asymmetry requires excellent proper time resolution.
- The decay time resolution is measured using the prompt $J/\psi+$ 2 charged tracks.
- **The effective decay time resolution measured is 39.8 fs in $J/\psi\pi^+\pi^-$ and $\sim$ 45 fs for $J/\psi\phi$.**





ϕ_s from $\overline{B}^0_s \to J/\psi\pi^+\pi^-$ analysis (I)

- Previous analysis was from $\overline{B}^0_s \to J/\psi f_0(980)$ decay. (**PL B707 (2012) 497**)
- Now use large range of $\pi^+\pi^-$ masses (775-1550 MeV).
- The final state of ϕ_s from $\overline{B}^0_s \to J/\psi\pi^+\pi^-$ is found to be almost pure CP-odd ($>$ 97.7% at 95% CL). (**arXiv:1204.5643, submitted to PRD**)
- This includes $f_0(980) + f_0(1370) + \pi^+\pi^-$ non − resonant components.
- 7421 ± 105 signal and 1717 ± 38 background events within 20 MeV of $\overline{B}^0_s$ mass peak, corresponds to 81% purity. (**arXiv:1204.5675, submitted to PLB**)



ϕ_s from $\overline{B}_s^0 \to J/\psi\pi^+\pi^-$ analysis (II)

- **No angular analysis is required as the final state is pure CP odd in $\overline{B}_s^0 \to J/\psi\pi^+\pi^-$ analysis.**
- The differential decay rate is straight forward:

$$\Gamma\left(B_s^0 \to J/\psi f_0\right) = \frac{\mathcal{N}}{2} e^{-\Gamma_s t}\{e^{\Delta\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Delta\Gamma_s t/2}(1-\cos\phi_s) - \sin\phi_s \sin(\Delta m_s t)\} \quad (2)$$

$$\Gamma\left(\overline{B}_s^0 \to J/\psi f_0\right) = \frac{\mathcal{N}}{2} e^{-\Gamma_s t}\{e^{\Delta\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Delta\Gamma_s t/2}(1-\cos\phi_s) + \sin\phi_s \sin(\Delta m_s t)\} \quad (3)$$

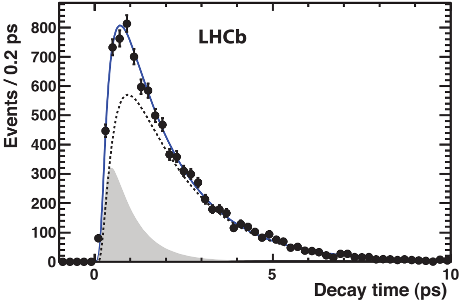
- The signal PDF is written as

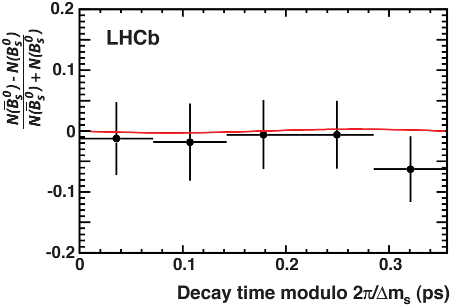
$$S(t;\phi_s) = \varepsilon(t) \times \left(\frac{1+qD}{2} s(t;\phi_s) + \frac{1-qD}{2}\overline{s}(t;\phi_s)\right) \bigotimes R(t), \quad (4)$$

where $\epsilon(t)$ = Proper time acceptance, control channel $B^0 \to J/\psi K^{*0}$,
q = tagging decision, $D = 1 - 2\omega$ and ω = mistag rate,
$R(t)$= Proper time resolution.

ϕ_s from $\overline{B}^0_s \to J/\psi\pi^+\pi^-$ analysis (III)

- $\Gamma_s = 0.657 \pm 0.009 \pm 0.008\ \mathrm{ps}^{-1}$ and $\Delta\Gamma_s = 0.123 \pm 0.029 \pm 0.011\ \mathrm{ps}^{-1}$ are constrained in fit, from previous LHCb measurement of $\overline{B}^0_s \to J/\psi\phi$ analysis (**PRL 108 (2012) 101803**).
- $\Delta m_s = 17.63 \pm 0.11 \pm 0.02\ \mathrm{ps}^{-1}$ also constrained from another LHCb measurement of $B^0_s \to D^-_s(3)\pi$ analysis (**PL B709 (2012) 177**).





$$\phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003}\ \mathrm{rad}$$

arXiv:1204.5675, submitted to PLB

ϕ_s from $B_s^0 \to J/\psi\phi$ analysis

- $B_s^0 \to J/\psi\phi$ is a P→VV decay, the final state is an admixture of CP-odd (L=1) and CP-even (L=0,2): $CP|J/\psi> = (-1)^L|J/\psi>$.
- The decay is described by 3 complex amplitudes: $A_0, A_{||}$ (CP-even) and $A_\perp$ (CP-odd).
- Non-resonant K^+K^- S-wave introduces another amplitude A_S (CP-odd).
- An **angular analysis** is required to disentangle the final states with the two different CP eigenvalues.
- LHCb uses the **transversity basis**: $\Omega = (\theta, \varphi, \psi)$. (definition of the angles are given in backup slide)
- Signal PDF is

$$S(t,\Omega;\overrightarrow{\lambda}) = \varepsilon(t,\Omega) \times \left(\frac{1+qD}{2} s(t,\Omega;\overrightarrow{\lambda}) + \frac{1-qD}{2} \overline{s}(t,\Omega;\overrightarrow{\lambda}) \right) \bigotimes R(t), \quad (5)$$

where $\overrightarrow{\lambda} = (\Gamma_S, \Delta\Gamma_s, \Delta m_s, \phi_s, |A_0|^2, |A_\perp|^2, \delta_{||}, \delta_\perp, |A_S|^2, \delta_s)$,

δ_0 is set to 0 and $|A_0(0)|^2 + |A_\perp(0)|^2 + |A_{||}(0)|^2 = 1$.

Differential decay rates

- The differential decay rate [+ for B_s^0 and - for $\overline{B}_s^0$]

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dtd\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega), \quad (6)$$

$$h_k(t) = N_k e^{-\Gamma_s t}\{a_k \cosh\frac{\Delta\Gamma_s t}{2} + b_k \sinh\frac{\Delta\Gamma_s t}{2} \pm c_k \cos(\Delta m_s t) \pm d_k \sin(\Delta m_s t)\} \quad (7)$$

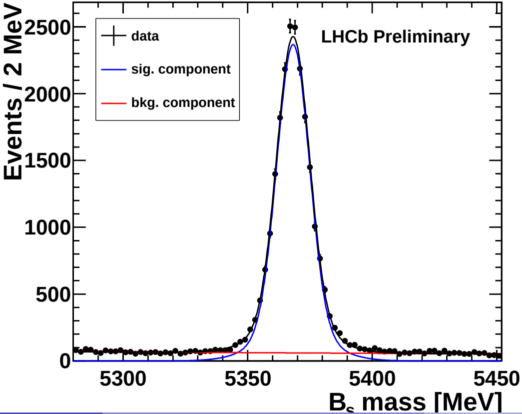
k	$f_k(\theta,\psi,\varphi)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\psi\,(1-\sin^2\theta\cos^2\phi)$	$\lvert A_0(0)\rvert^2$	1	$-\cos\phi_s$	0	$\sin\phi_s$
2	$\sin^2\psi\,(1-\sin^2\theta\sin^2\phi)$	$\lvert A_\parallel(0)\rvert^2$	1	$-\cos\phi_s$	0	$\sin\phi_s$
3	$\sin^2\psi\sin^2\theta$	$\lvert A_\perp(0)\rvert^2$	1	$\cos\phi_s$	0	$-\sin\phi_s$
4	$-\sin^2\psi\sin 2\theta\sin\phi$	$\lvert A_\parallel(0)A_\perp(0)\rvert$	0	$-\cos(\delta_\perp-\delta_\parallel)\sin\phi_s$	$\sin(\delta_\perp-\delta_\parallel)$	$-\cos(\delta_\perp-\delta_\parallel)\cos\phi_s$
5	$\frac{1}{2}\sqrt{2}\sin 2\psi\sin^2\theta\sin 2\phi$	$\lvert A_0(0)A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$-\cos(\delta_\parallel-\delta_0)\cos\phi_s$	0	$\cos(\delta_\parallel-\delta_0)\sin\phi_s$
6	$\frac{1}{2}\sqrt{2}\sin 2\psi\sin 2\theta\cos\phi$	$\lvert A_0(0)A_\perp(0)\rvert$	0	$-\cos(\delta_\perp-\delta_0)\sin\phi_s$	$\sin(\delta_\perp-\delta_0)$	$-\cos(\delta_\perp-\delta_0)\cos\phi_s$
7	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$	$\lvert A_S(0)\rvert^2$	1	$\cos\phi_s$	0	$-\sin\phi_s$
8	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$	$\lvert A_S(0)A_\parallel(0)\rvert$	0	$-\sin(\delta_\parallel-\delta_S)\sin\phi_s$	$\cos(\delta_\parallel-\delta_S)$	$-\sin(\delta_\parallel-\delta_S)\cos\phi_s$
9	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$	$\lvert A_S(0)A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$\sin(\delta_\perp-\delta_S)\cos\phi_s$	0	$-\sin(\delta_\perp-\delta_S)\sin\phi_s$
10	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$	$\lvert A_S(0)A_0(0)\rvert$	0	$-\sin(\delta_0-\delta_S)\sin\phi_s$	$\cos(\delta_0-\delta_S)$	$-\sin(\delta_0-\delta_S)\cos\phi_s$

only 7th term presents in $J/\psi\pi^+\pi^-$ analysis.

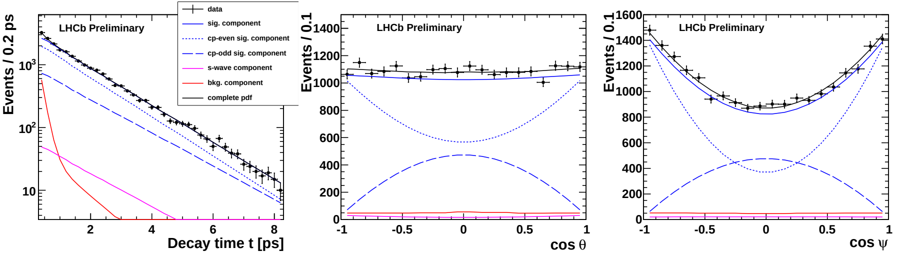
This is important for resolving the two fold ambiguity.

$\overline{B}_s^0 \to J/\psi\phi$ signal

- Full 2011 data set of 1 fb^{-1} is used (LHCb-CONF-2012-004).
- Simple cut selections.
- Most background removed by decay time cut $t > 0.3$ ps.
- Very clean signal$\sim$ 21200 signal candidates. (LHCb Preliminary)

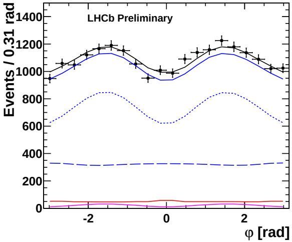


Decay time and angular distributions



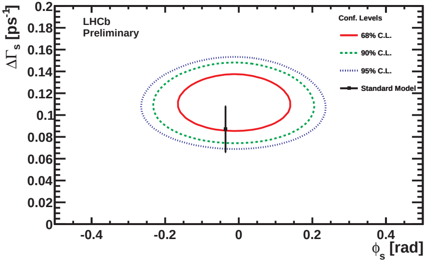
- Decay time and angular distributions and the fitted PDF.
- CP-even and CP-odd separation is very clear.
- Fraction of K^+K^- S-Wave within ± 12 MeV of $\phi(1020)$ peak. (LHCb-CONF-2012-004).

$$F_s = (2.2 \pm 1.2 \pm 0.7)\% \text{ (LHCb Preliminary)}$$



CP violation in $B_s^0 \to J/\psi\phi$

- Full fit to the B_s^0 mass, decay time and angular distributions are used.
- Δm_s is constrained in the fit.



(LHCb-CONF-2012-004, LHCb Preliminary)

  - $\phi_s = -0.001 \pm 0.101 \pm 0.027$ rad
  - $\Gamma_s = 0.6580 \pm 0.0054 \pm 0.0066$ ps^{-1}
  - $\Delta\Gamma_s = 0.116 \pm 0.018 \pm 0.006$ ps^{-1}

- **$\Delta\Gamma_s$ is the first observed non-zero value. All the measurements are compatible with SM.**

Combined results from $B_s^0 \to J/\psi\pi^+\pi^-$ & $B_s^0 \to J/\psi\phi$

- Simultaneous fit to both $B_s^0 \to J/\psi\pi^+\pi^-$ & $B_s^0 \to J/\psi\phi$ gives

$$\phi_s = -0.002 \pm 0.083 \pm 0.027 \text{ rad}$$

LHCb-CONF-2012-004, LHCb Preliminary

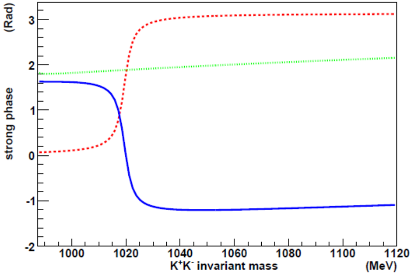
- The Result is in very good agreement with the SM

$$\phi_s = -0.036 \pm 0.002 \text{ rad}$$

- However the experimental error (0.083) is much larger than the SM value. We need more statistics.
- We will have 5X data before upgrade!
- Other modes for example $B_s^0 \to \psi(2S)\phi,\ J/\psi\eta'$ are being pursued to improve the precision and for cross check.

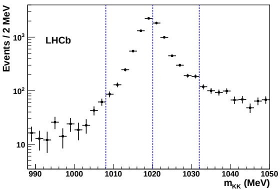
Resolve ambiguity (I)

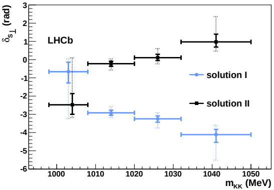
- There are two ambiguous solutions related by $(\phi_s, \Delta\Gamma_s, \delta_{||}, \delta_\perp, \delta_s) \Longleftrightarrow (\pi - \phi_s, -\Delta\Gamma_s, -\delta_{||}, \pi - \delta_\perp, -\delta_s)$. JHEP 0909:74,2009
- The interference between the K^+K^- S-wave and P-wave amplitudes in $B_s^0 \to J/\psi K^+K^-$ decays with K^+K^- pairs in the region around $\phi(1020)$ resonance is used to resolve the ambiguity.
- Phase of Breit-Wigner amplitude increases rapidly across $\phi(1020)$ mass pole.
- Phase of amplitude for Flatte $f_0(980)$ or non-resonance is relatively flat in $\phi(1020)$ mass region.
- **Physical Solution:** the one which has decreasing trend of $\delta_S - \delta_P$ with $m(K^+K^-)$ in $\phi(1020)$ mass region



Resolve ambiguity (II)

- Measurements use 0.37 fb^{-1} of LHCb data. **arXiv 1202:4717, submitted to PRL**
- Split data into 4 bins of $m(K^+K^-)$.
- In each bin we measured the fraction of S-wave and $\delta_{S\perp} = \delta_S - \delta_\perp$.

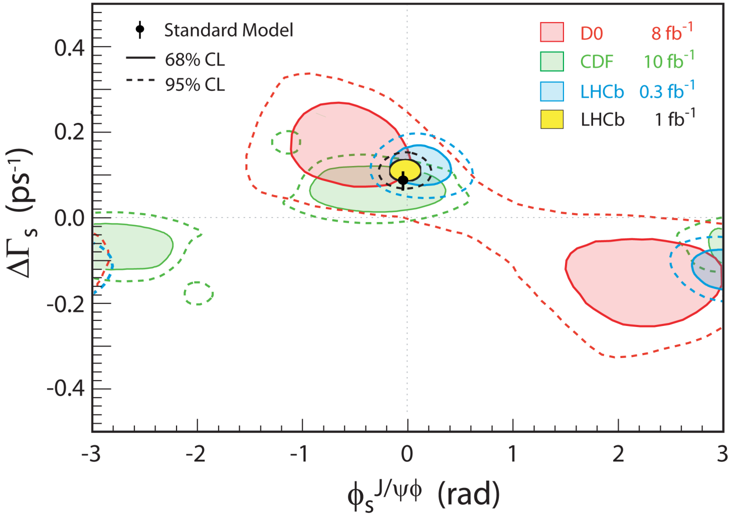




Parameter	Solution I	Solution II
ϕ_s (rad)	0.167 ± 0.175	2.975 ± 0.175
$\Delta\Gamma$ (ps^{-1})	0.120 ± 0.028	-0.120 ± 0.028
$F_{S;1}$	0.283 ± 0.113	0.283 ± 0.113
$F_{S;2}$	0.061 ± 0.022	0.061 ± 0.022
$F_{S;3}$	0.044 ± 0.022	0.044 ± 0.022
$F_{S;4}$	0.269 ± 0.067	0.269 ± 0.067
$\delta_{S\perp;1}$ (rad)	$-0.46\,^{+0.35}_{-0.42}$	$-2.68\,^{+0.42}_{-0.35}$
$\delta_{S\perp;2}$ (rad)	$-2.92\,^{+0.15}_{-0.13}$	$-0.22\,^{+0.13}_{-0.15}$
$\delta_{S\perp;3}$ (rad)	$-3.25\,^{+0.16}_{-0.18}$	$0.11\,^{+0.18}_{-0.16}$
$\delta_{S\perp;4}$ (rad)	$-4.11\,^{+0.28}_{-0.43}$	$0.97\,^{+0.43}_{-0.28}$

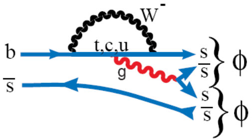
- **$\delta_{S\perp}$ decreases for solution I with $\Delta\Gamma_s > 0$ at 4.7 σ**

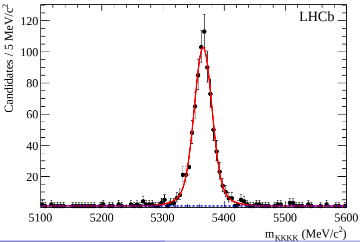
Pictorial overlay



$B_s^0 \to \phi\phi$

- This is another P→VV decay. The amplitude for the decay is dominated by gluonic-penguin quark transitions, sensitive to the study beyond the SM.
- In this decay the decay phase cancels the mixing phase if only SM particles are involved, so this is an interesting place to look for manifestations of new physics.
- Very clean signal (801 ± 29) is observed at $1\ \mathrm{fb}^{-1}$. (**arXiv:1204.2813, submitted to PLB**)
- Larger dataset is needed for ϕ_s measurement. This mode will be a key channel for LHCb upgrade.





Conclusions

- LHCb is performing well, gives most precise measurement for ϕ_s.
- Resolve the ambiguity on the sign of $\Delta\Gamma_s$.
- TD CPV gives no evidence yet for New Physics in ϕ_s measurements.
- Lots of ongoing work ...
  ... ... we hope to see NEW PHYSICS soon.

Thank you

Back Up

Transversity Basis